Focused Schlieren Imaging for Supersonic Film Cooling

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THERMAL & FLUIDS ANALYSIS WORKSHOP
GSFC · 2015

Outline

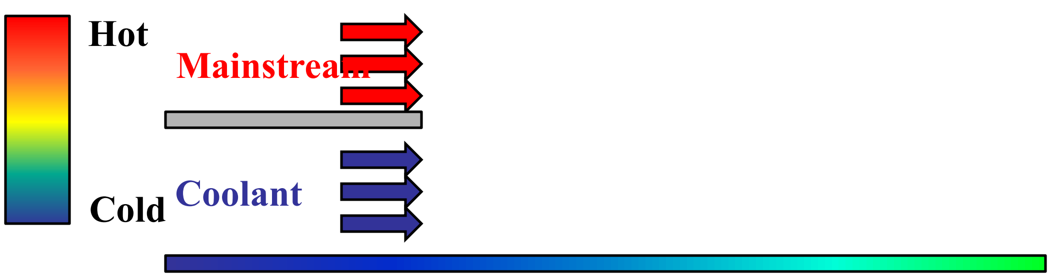
- **Background**
- **Objectives and Methodology**
- **Results and Conclusions**

Introduction to Film Cooling

What is Film Cooling?

- Technique where a cooler gas is injected along critical surfaces, creating an insulating layer that protects the walls from hot combustion exhaust.

- **Applications**
  - Gas Turbines
    - Combustor liner
    - Turbine blades
  - Rockets
    - Nozzle extension



Film Cooled Wall

Gas turbine combustor

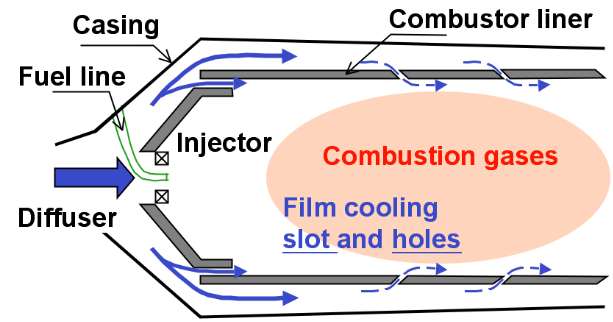
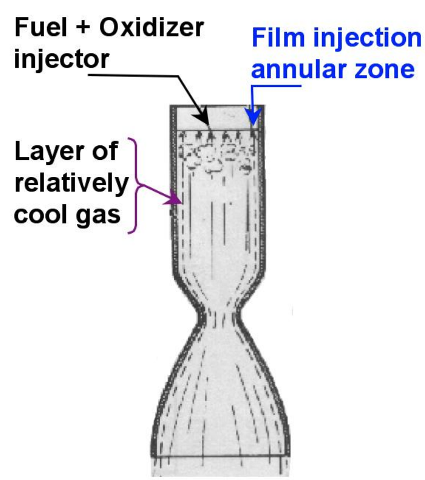


Figure Adapted from Cruz (2008)

Rocket thrust chamber

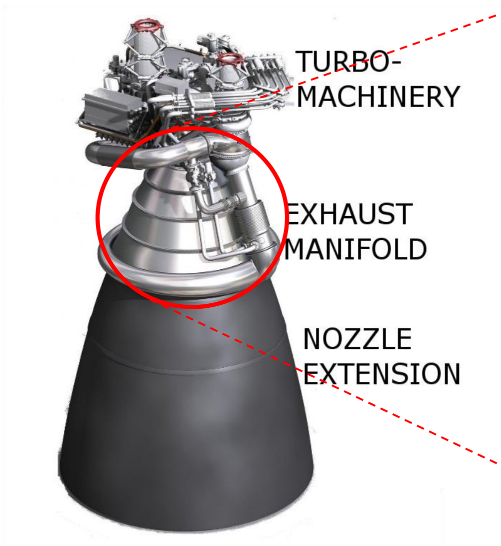


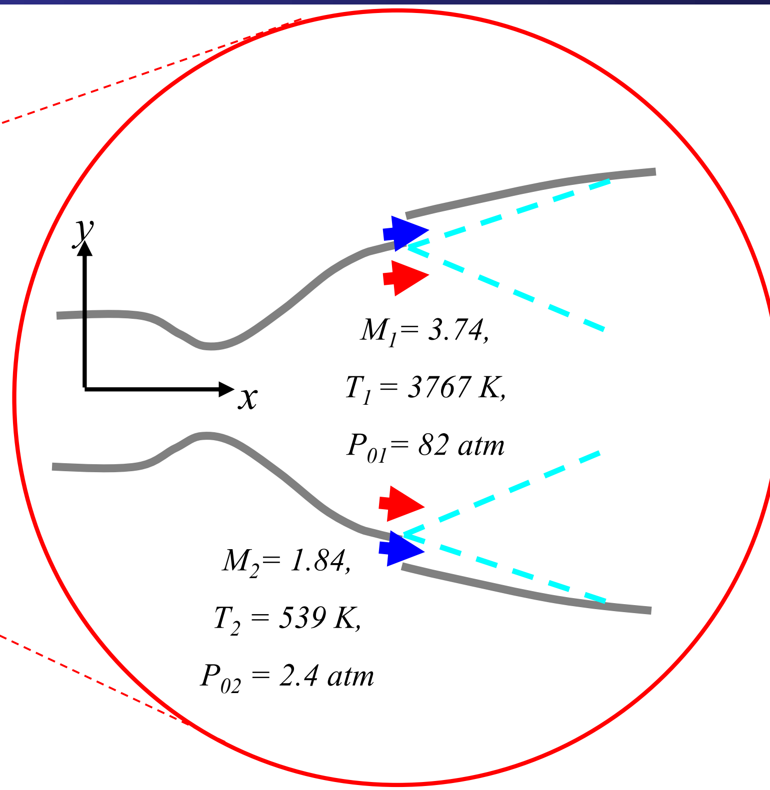
Adapted from (Sutton, 1986)

J-2X Concept

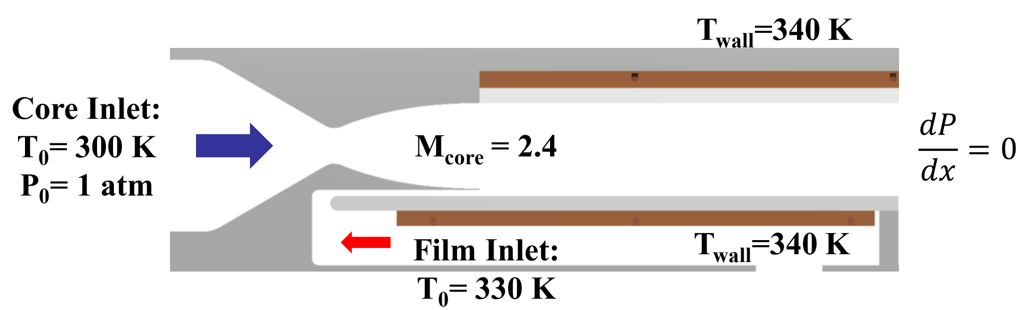
J-2x Nozzle film Cooling

- J-2X nozzle extension





- UMD tunnel
  - J-2X analogue
  - Various film flow cases:
    - Case 0 – no film
    - Case 1 – $M_{film} = 0.5$
    - Case 2 – $M_{film} = 0.7$
    - Case 3 – $M_{film} = 1.2$



Physics of Film Cooling

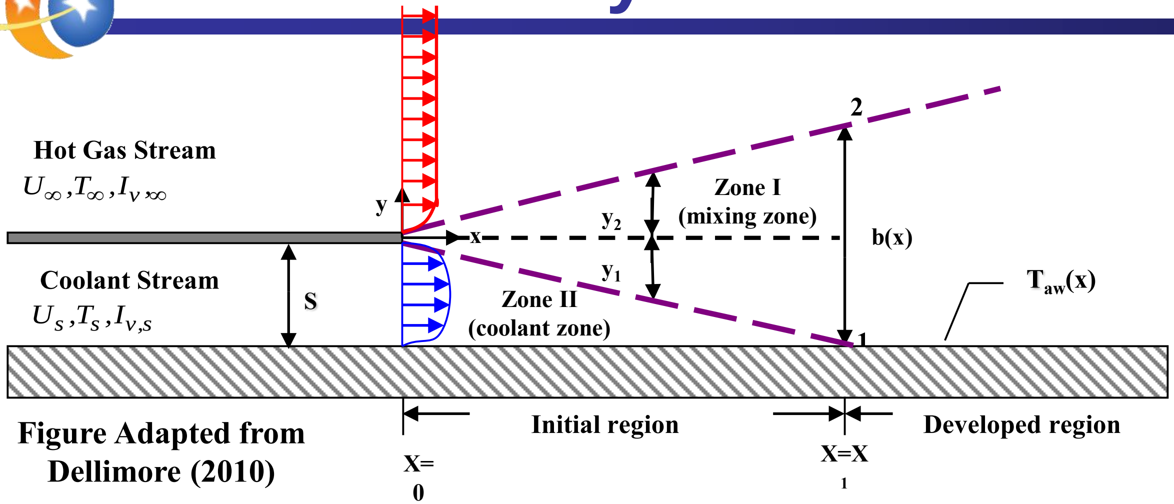


Figure Adapted from Dellimore (2010)

Important Flow Features

- Large Shear
- Wall-bounded flow
- Initial turbulence
- Intense mixing and heat transfer
- Low pressure region behind louver lip

Parameters characterizing the mixing of the film

- Blowing ratio, $BR = (\rho U)_s / (\rho U)_\infty$
- Velocity ratio, $VR = U_s / U_\infty$
- Slot Reynolds number, $Re_s = (U_s\, s)/\nu$
- Inlet turbulence intensity, $I_u = U_{rms}/U$, $I_v = V_{rms}/U$

Wall Wake (WW) – VR < 1

Minimum Shear (MS) – VR ~ 1

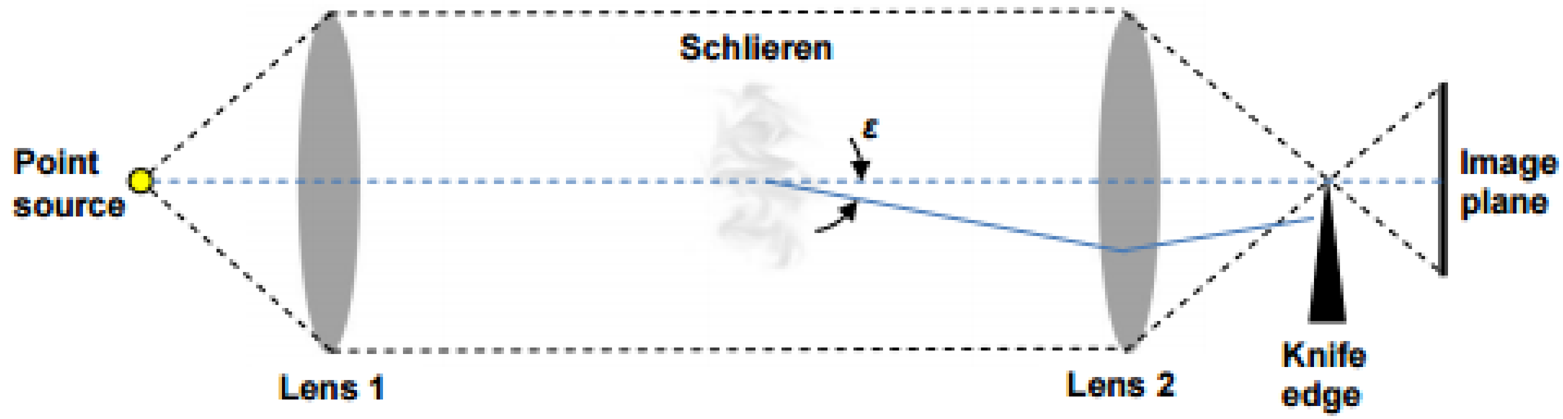
Wall Jet (WJ) – VR > 1

Film Cooling effectiveness

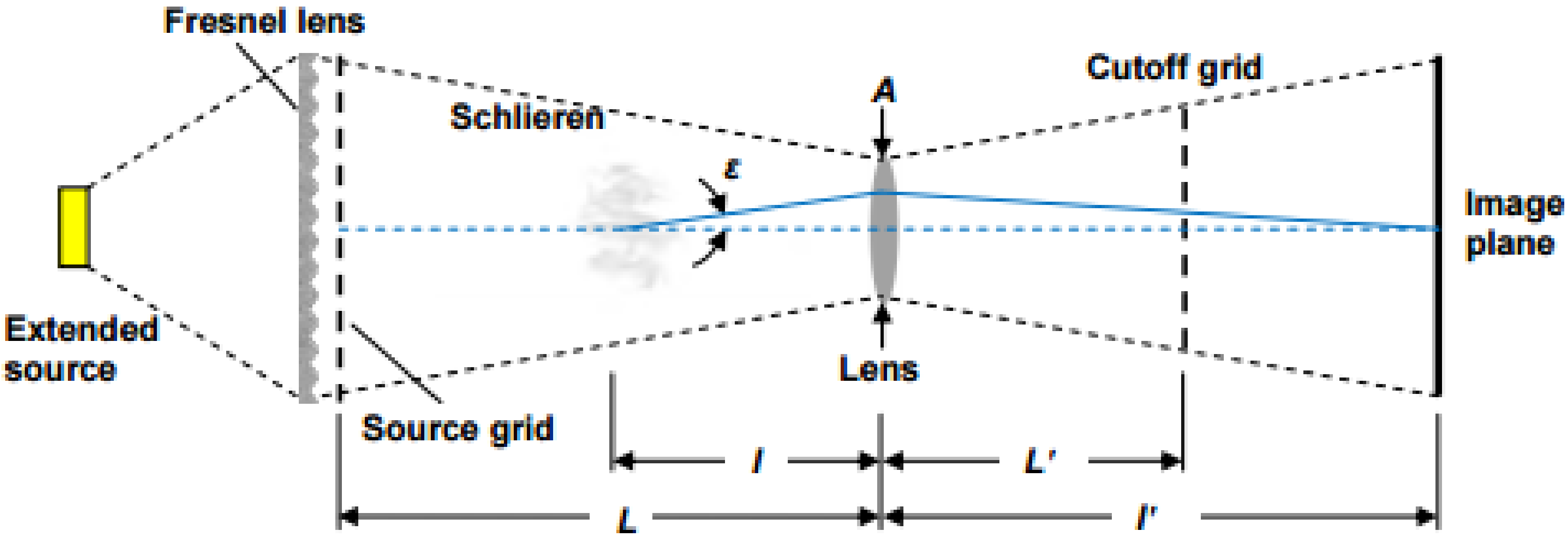
$$\boxed{\eta_{aw} = \frac{(T_\infty - T_{aw})}{(T_\infty - T_c)}}$$

Regular vs Focused Schlieren Schematic

Regular

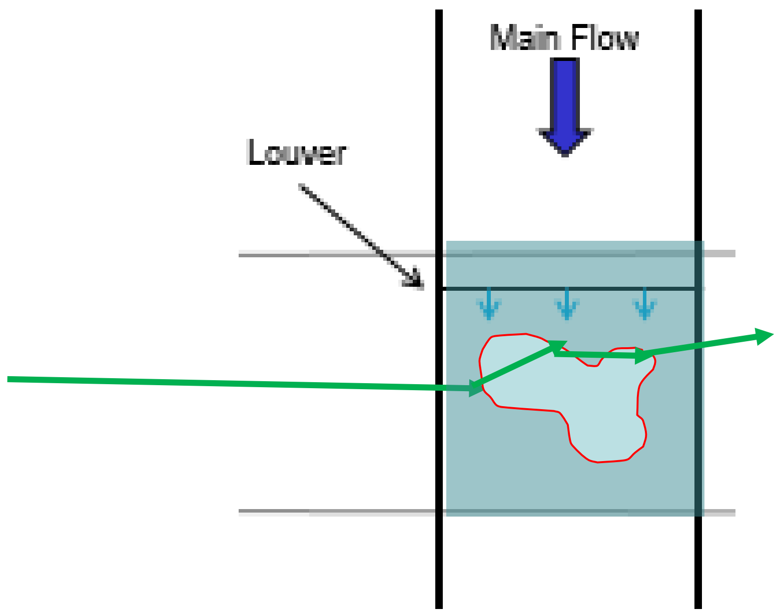


Focused

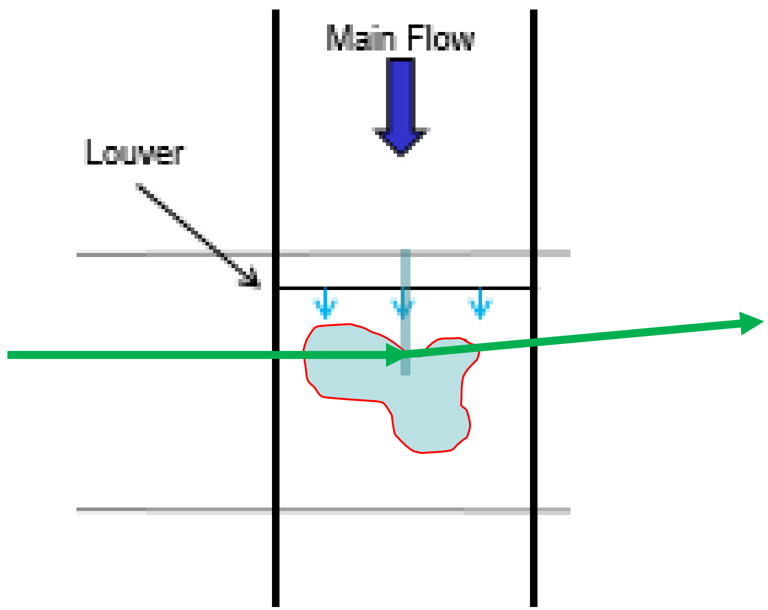


Depth of Focus

Regular

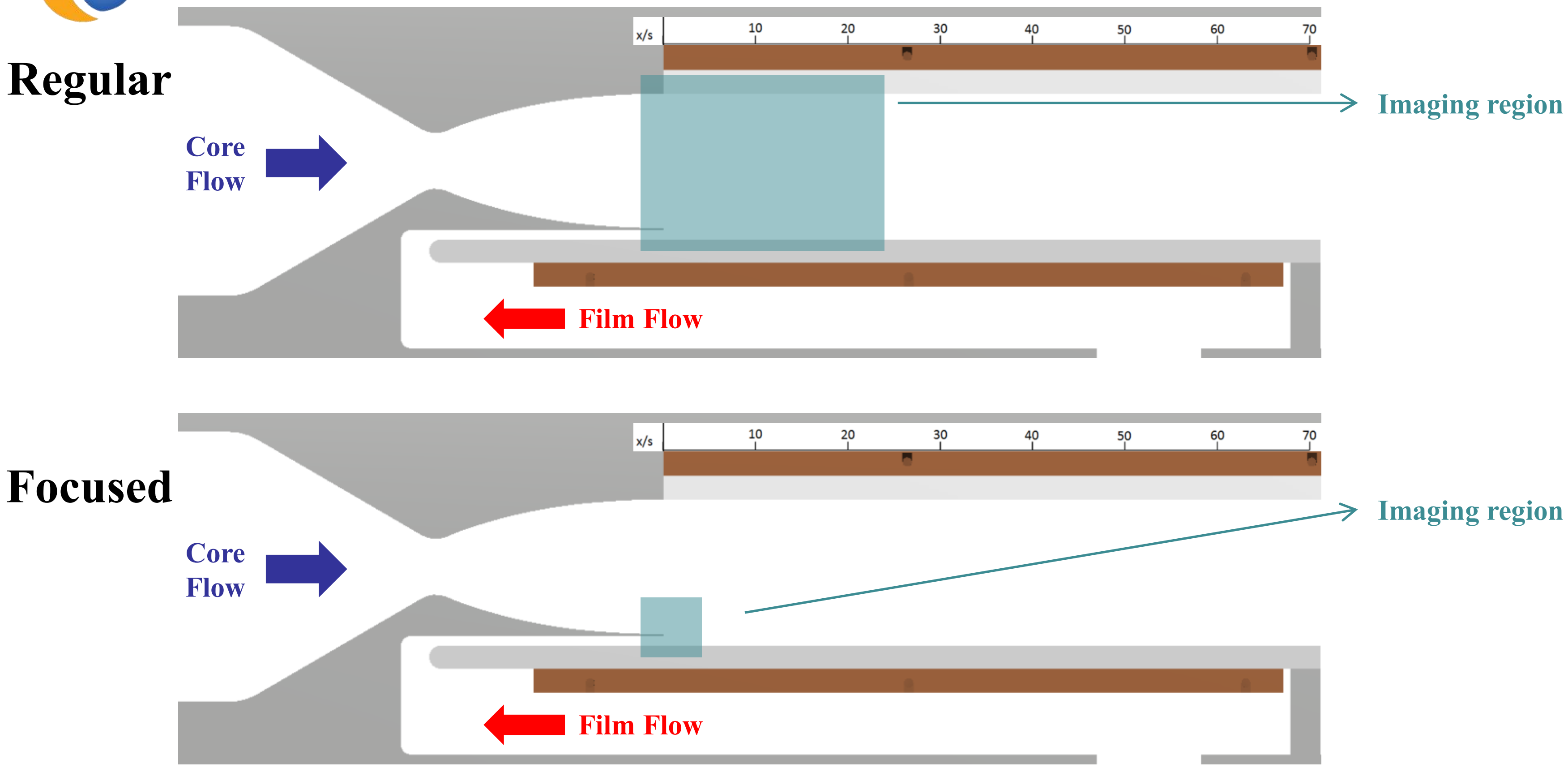


Focused



The resulting image will be the average of all planes within depth of focus. Will only be able to see turbulent structures with focused schlieren

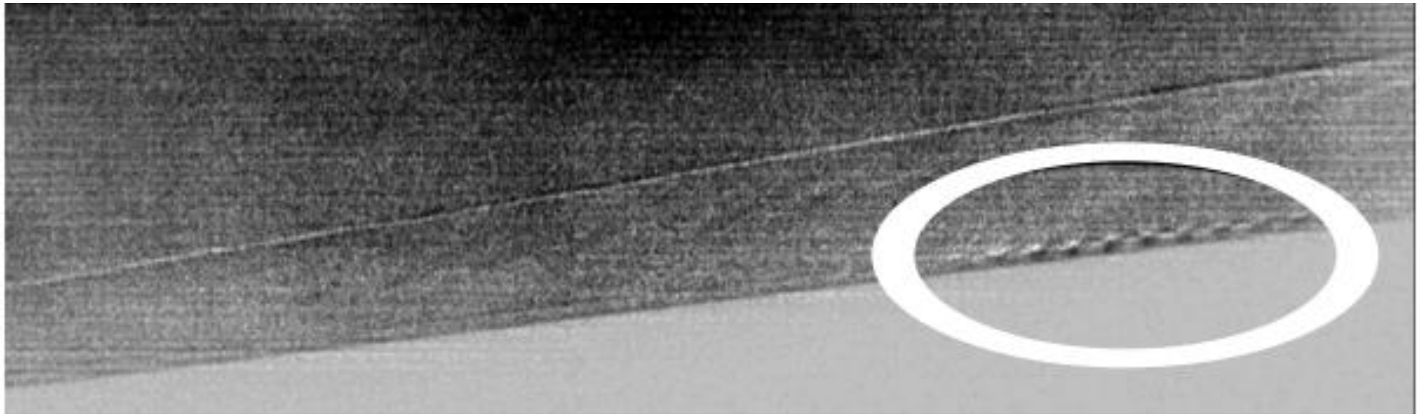
Field of View



- Focused Schlieren has a much smaller Field of view

Previous Work

- VanDercreek[1] was able to visualize a turbulent boundary layer on a sharp nosed cone in a hypersonic wind Tunnel



- Lawson[2] was able to measure velocity of supersonic turbulent boundary layer using focusing-schlieren PIV with a pulsed LED

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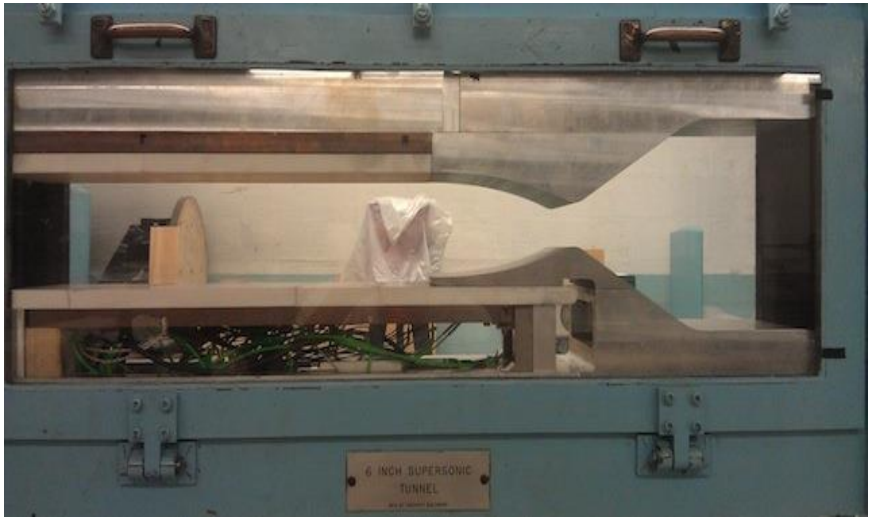
Objectives

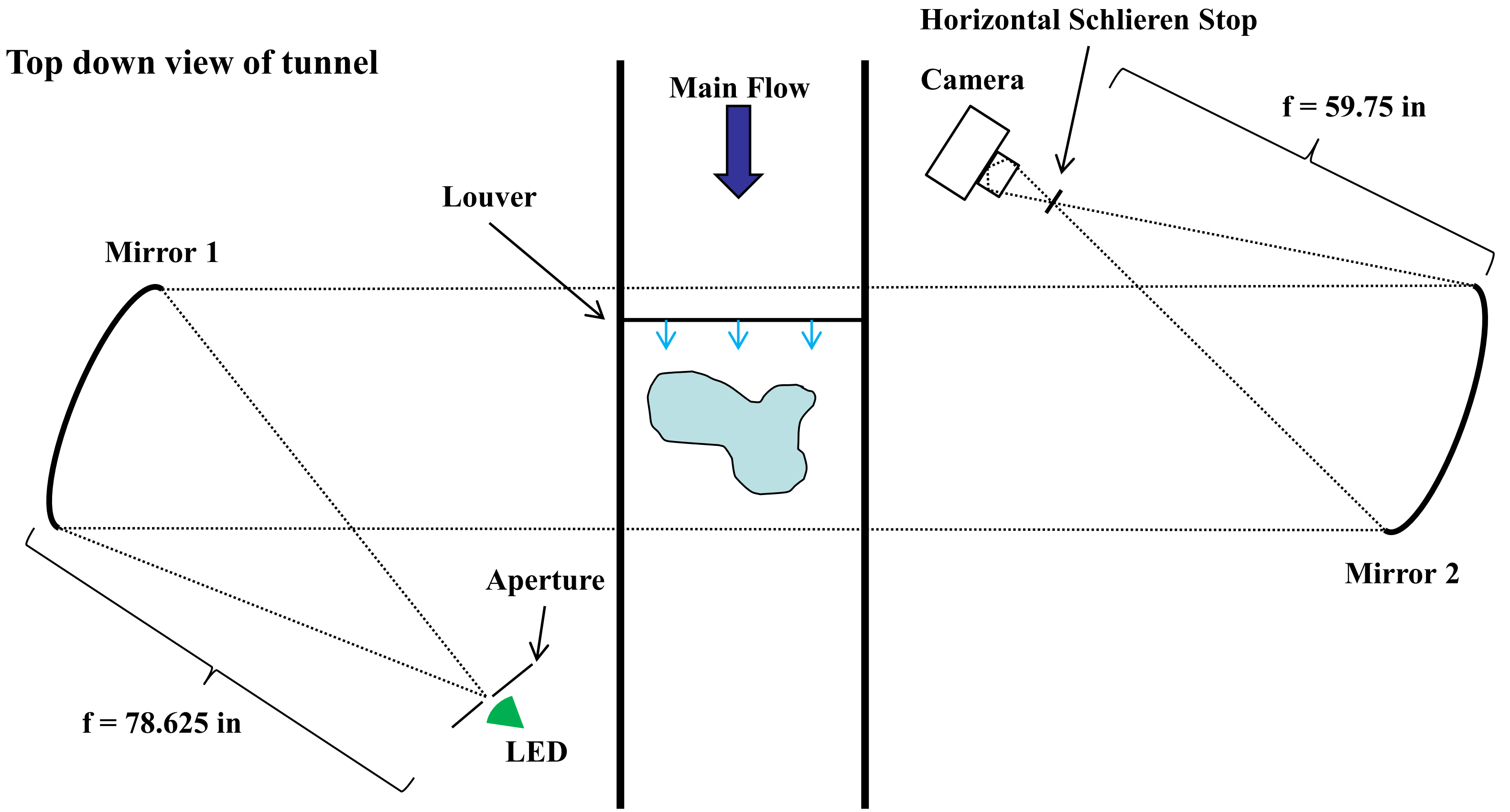
- A non-Intrusive method to resolve velocity field and flow structures
  - Use regular schlieren to visualize shocks and expansions
  - Used focused schlieren to visualize turbulent structures in the boundary layer
  - Use a pulsed LED for focused schlieren PIV
    - Freeze flow to move only 0.1 mm
- Compare experimental velocity and flow structures to CFD for validation

UMD Supersonic Wind Tunnel



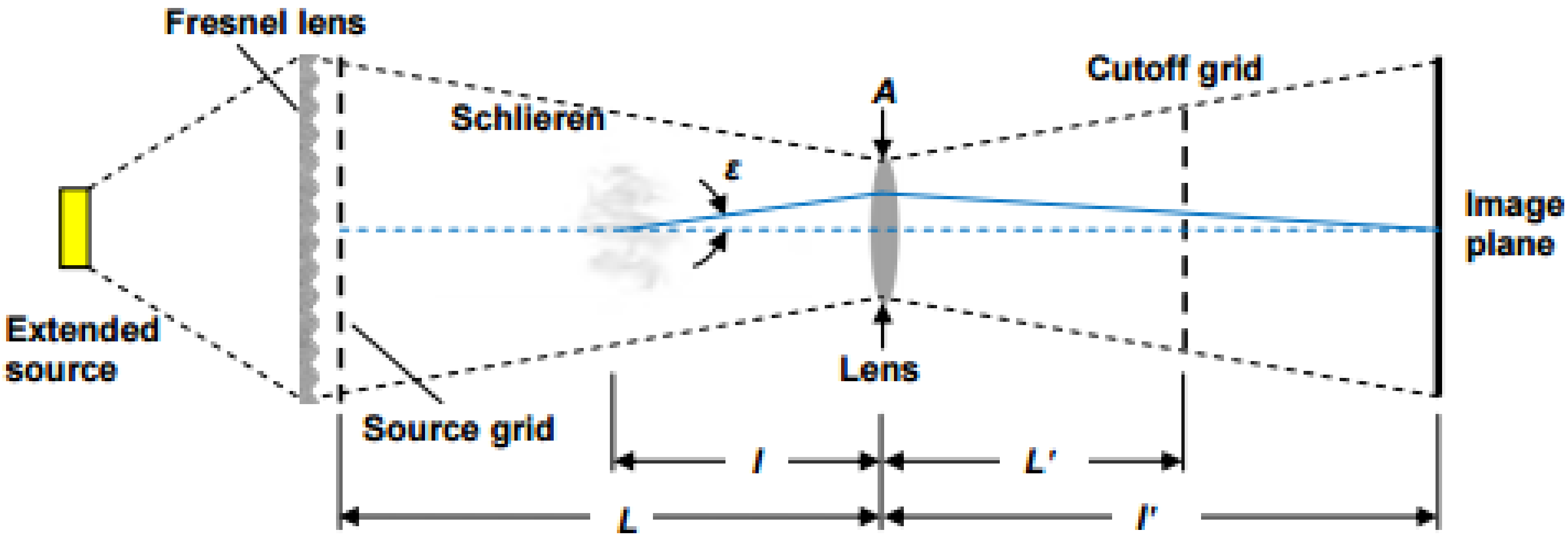
- Basic Specs
  - Transient facility (6-10 sec run time)
  - Working fluid: Air
  - Total P, T: Ambient
  - Test section Dimension: 12”x6”x26”
- The tunnel cannot directly match J-2X conditions so special care must be taken to design analogous experiments.
  - Heat walls to ensure that the heat flux vector always points into the flow
  - Heat film to ensure temperature “cascade” is preserved

Schlieren System



- Z configuration
- Nikon D-90 with Nikon 70-300mm f/4-5.6G lens

Focused Schlieren Lengths

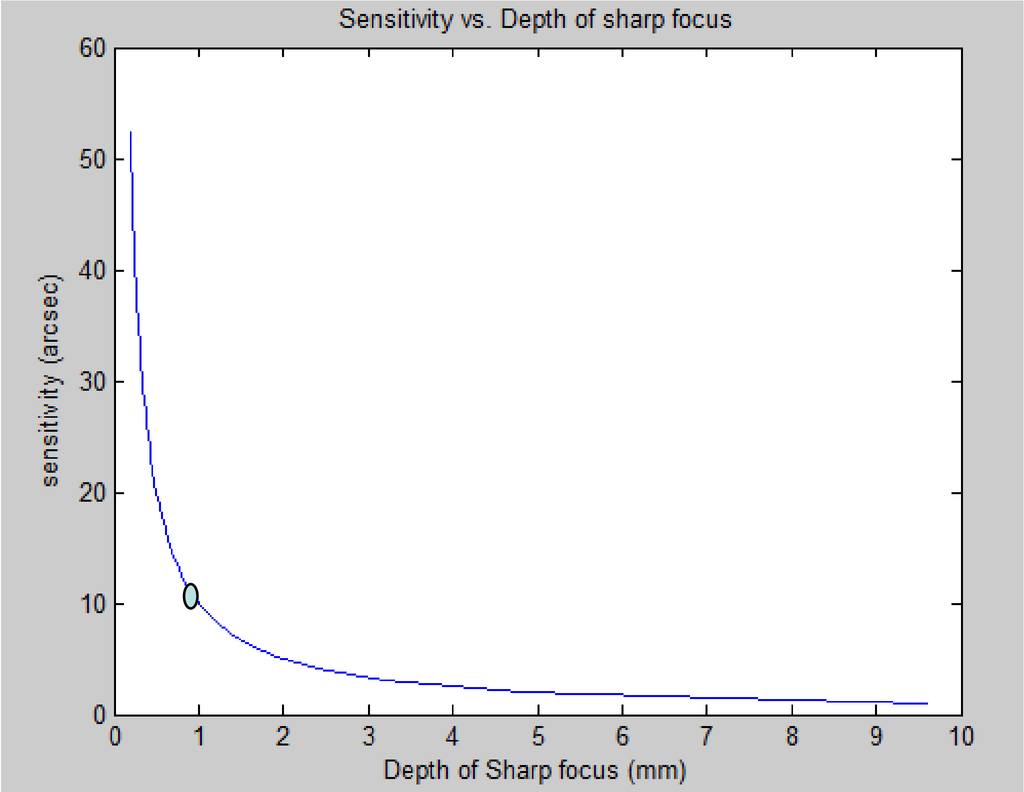


- Everything was kept symmetric
  - L=l' =1219 mm
  - l =L' = 240 mm. Determined by focal length of schlieren Lens

Cut-off grid Calculations

$$\epsilon_{min} = 20626 * \frac{b}{2} * \frac{L}{L' * (L - l)} = 10\ arcseconds$$

$$Ds = \frac{4 * l^2 * (l' - L') * \lambda}{A_s\ * b\ * l'} = 1\ mm$$

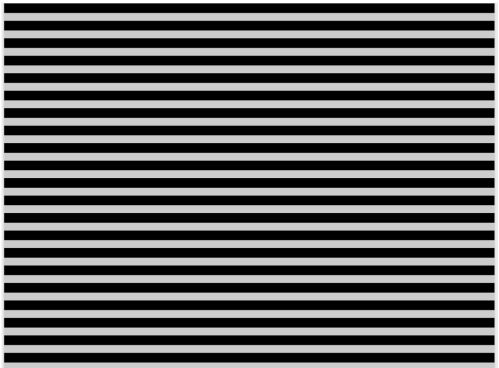


λ = wavelength of light = $521 * 10^{-6}\ mm$

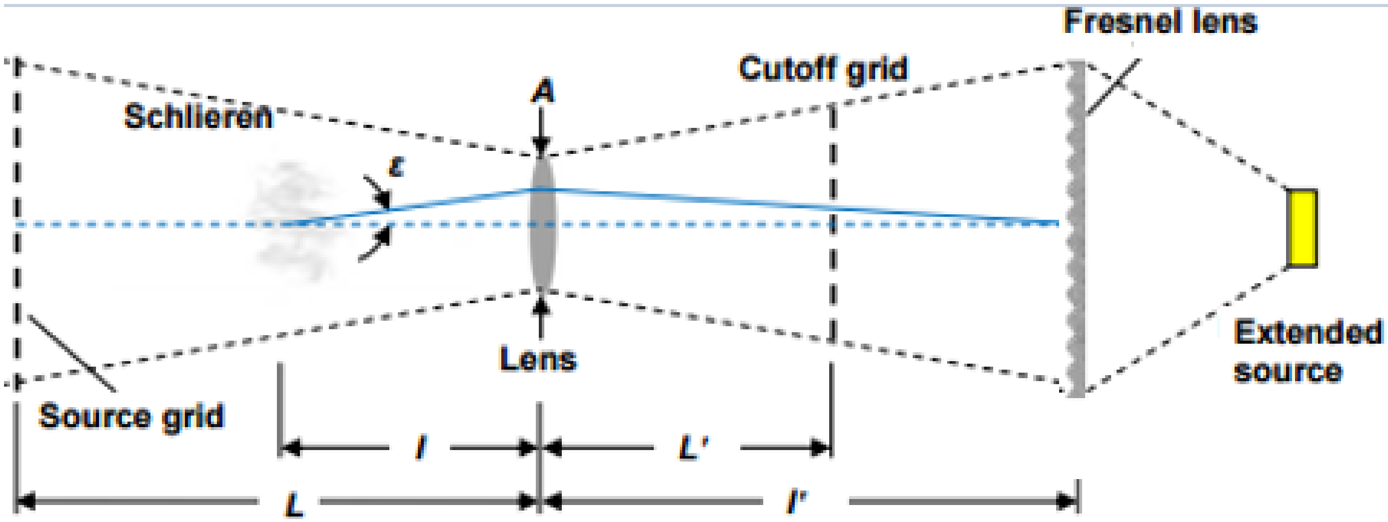
As = Schlieren lens diameter = 100 mm

$b = cutoff\ grid\ width = 1mm$

Cut-Off grid



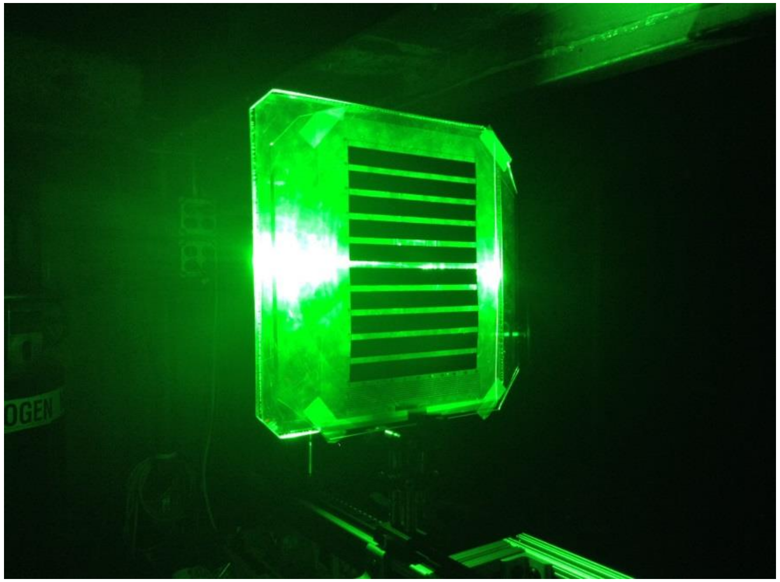
Generating Source Grid



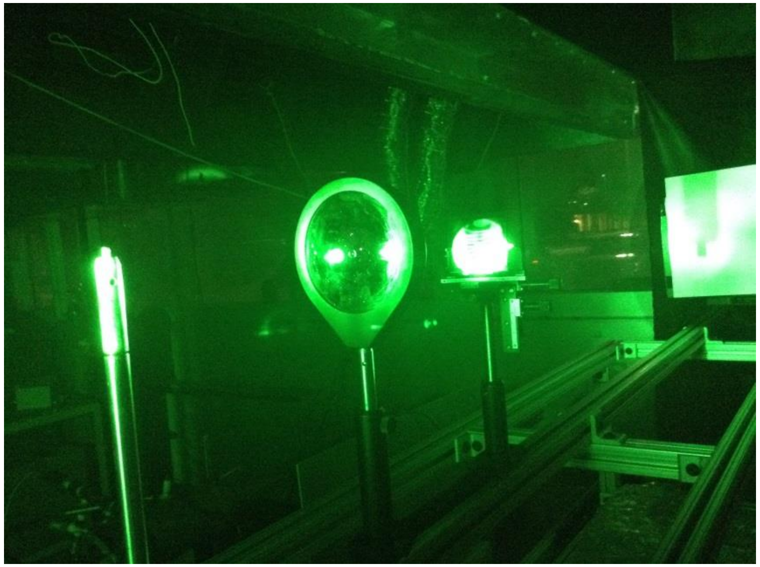
- System is symmetric. So able to run system in reverse in order to determine size of source grid
- Both cut-off and source grid printed on transparency paper

Focused Schlieren System

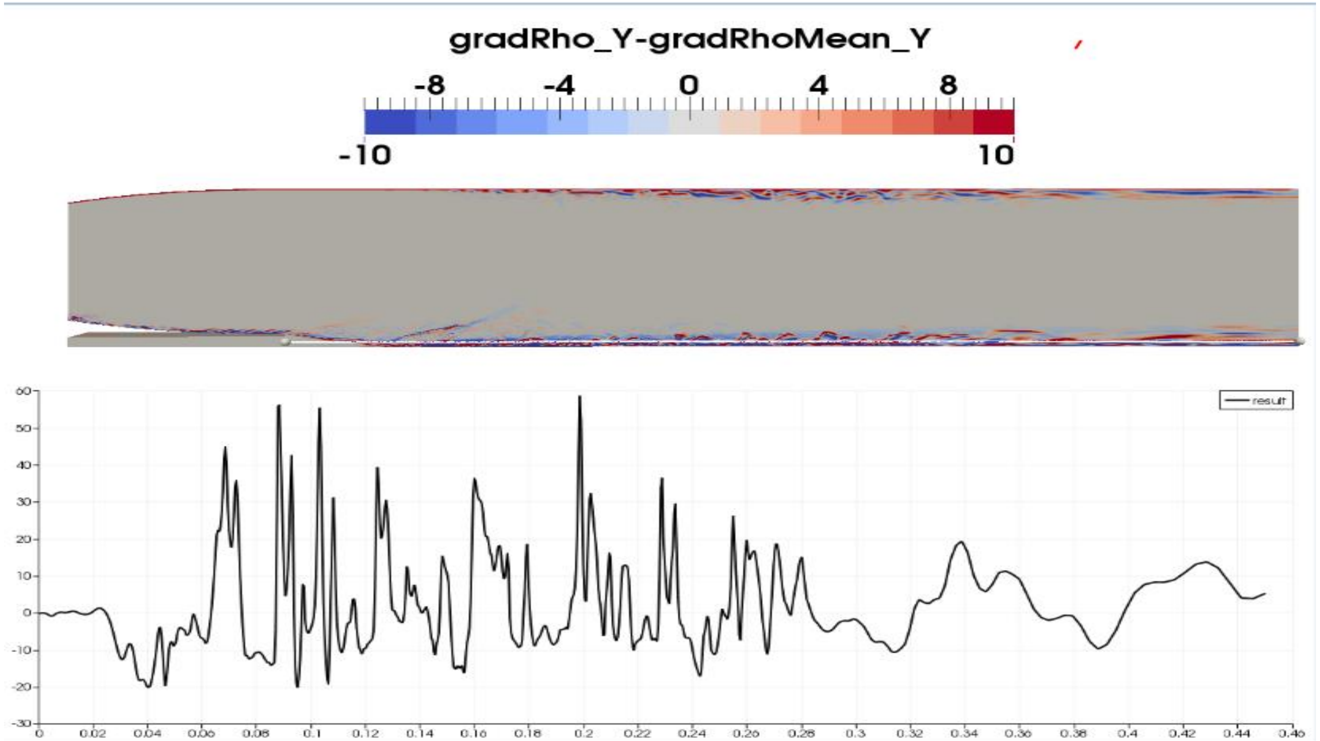
Fresnel Lens and Source Grid



Schlieren Lens and cut-off grid



Expected Focused Schlieren Images



$$k = Gladstone - Dale\ coefficient = 0.23\,\frac{cm^3}{g}$$

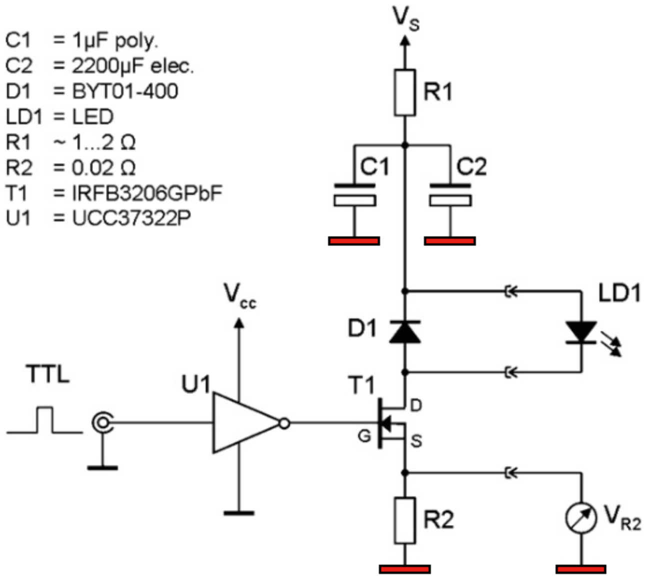
$$n_0 = 1.000292\ for\ air$$

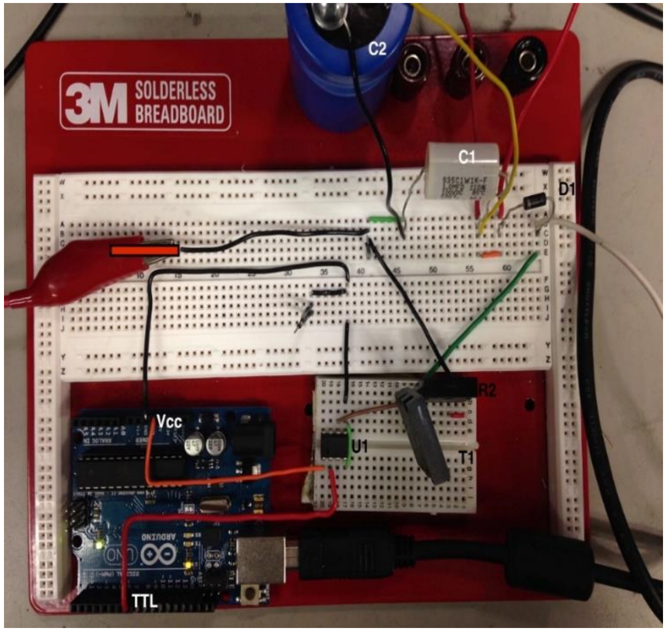
$$\epsilon_y = \frac{k * L}{n_0}\frac{\partial \rho}{\partial y};$$

Can view Density Gradients :

$$|\nabla \rho| > 0.88\,\frac{kg}{m^4}$$

Pulsed Light Source





- Based on a high intensity LED with an advertised response time < 25 ns
- Based on Wilert's design[3] which used a pulse width of $5\mu s$
- Circuit triggered using a square wave generated by an Arduino
  - Arduino provides inexpensive triggering flexibility

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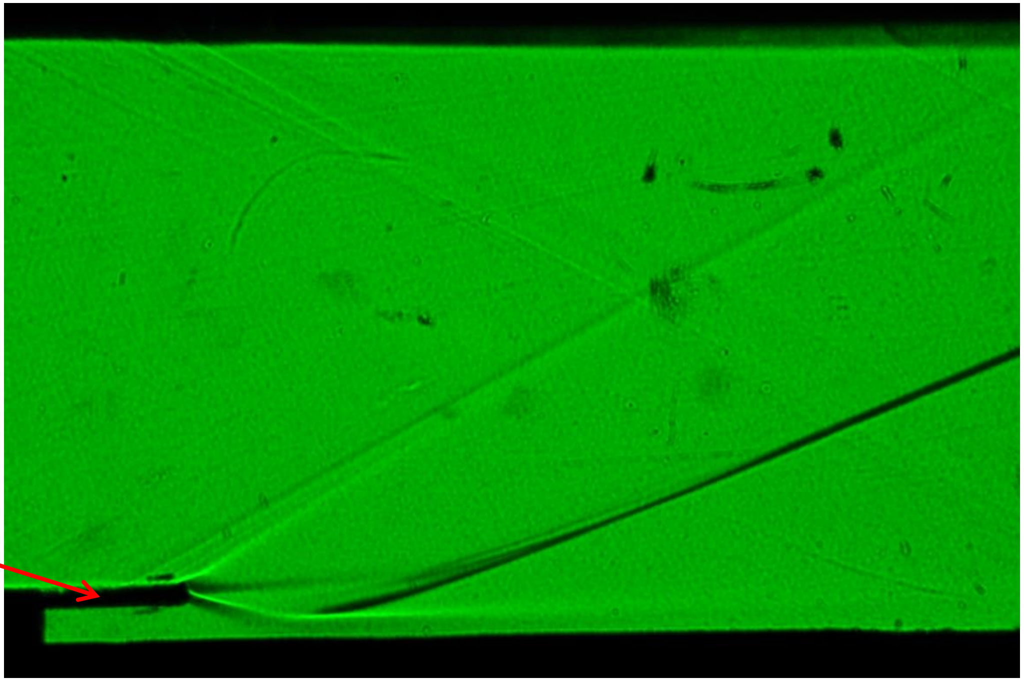
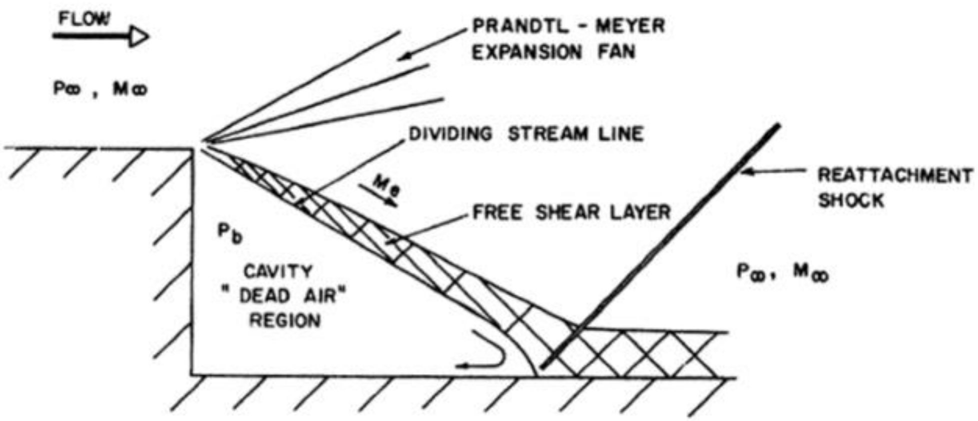
Flow Structure: Case 0 ($M_{film} = 0$)

Flow

Film Louver

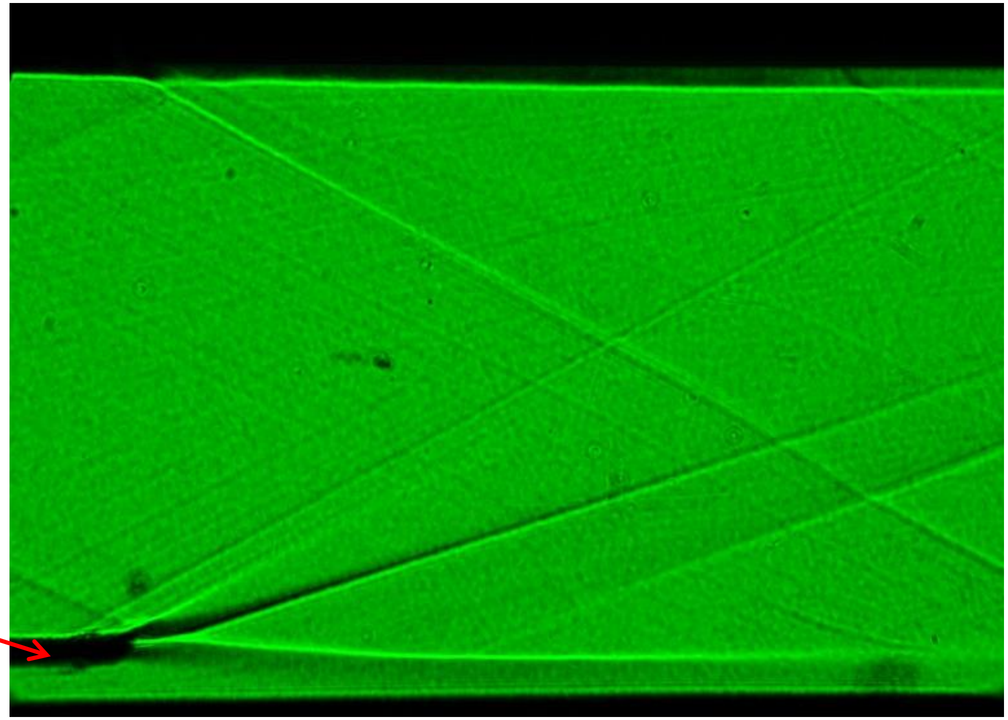


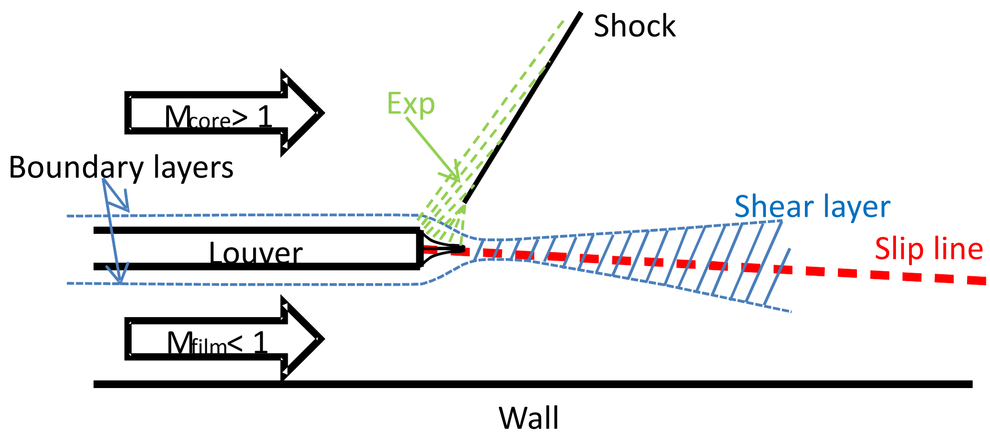


Flow Structure: Case 1 ($M_{film} = 0.5$)

Flow

Film Louver

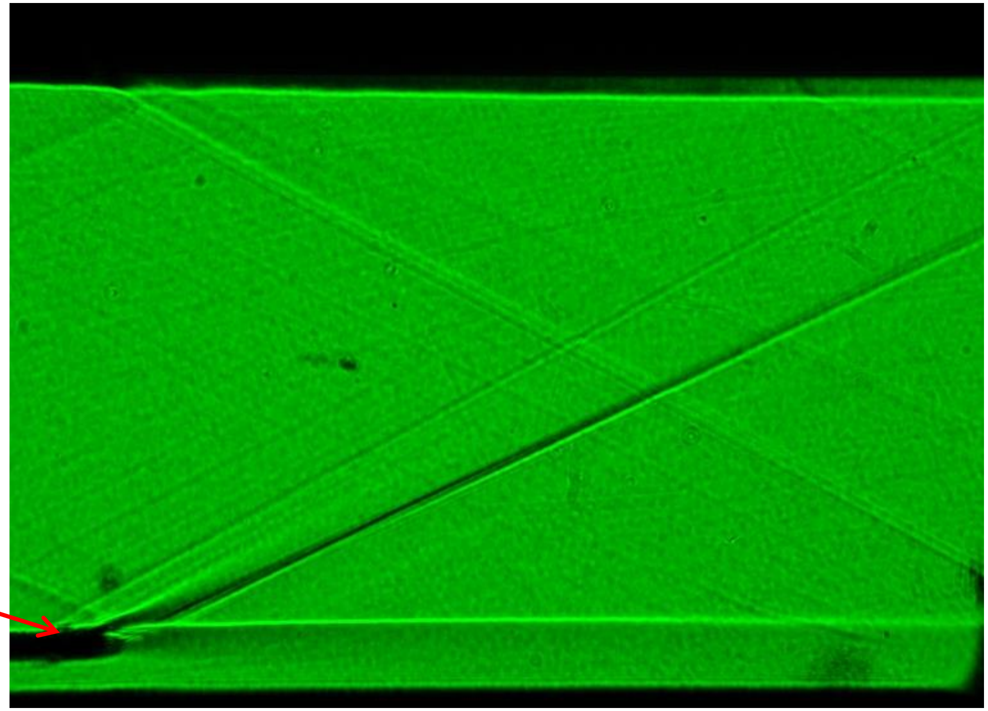


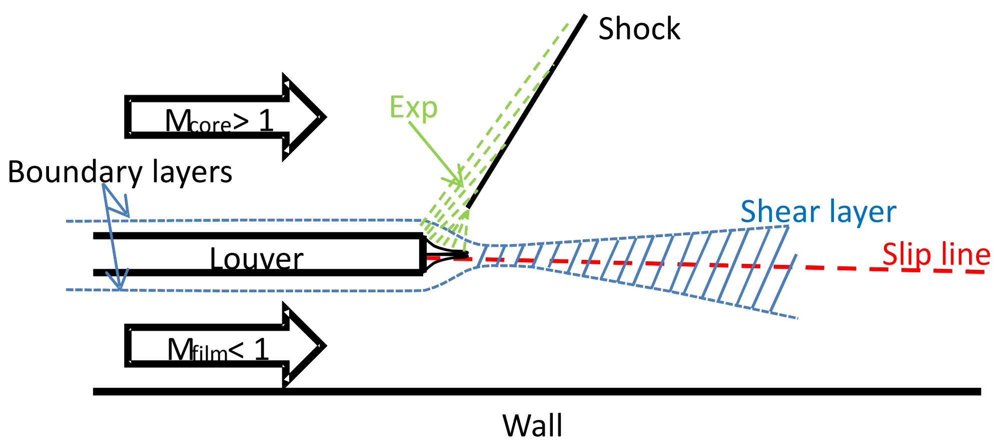


Flow Structure: Case 2 ($M_{film} = 0.7$)

Flow

Film Louver

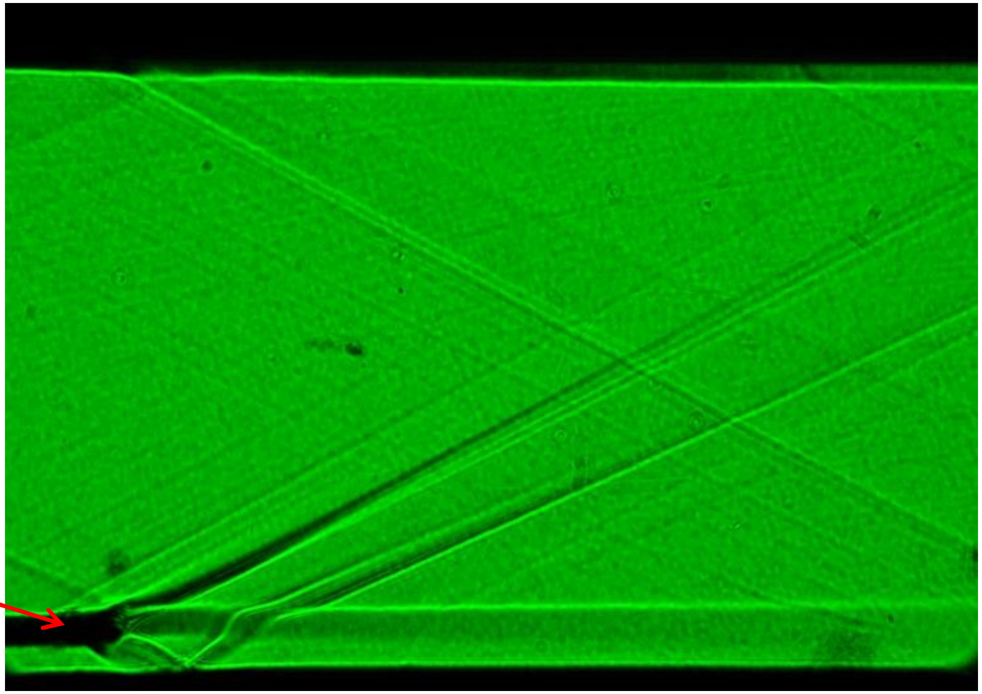


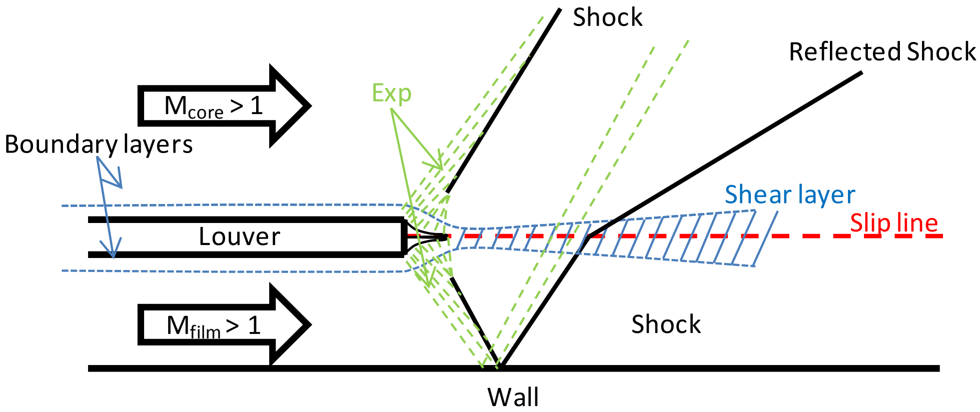


Flow Structure: Case 3 (M_{film} = 1.2)

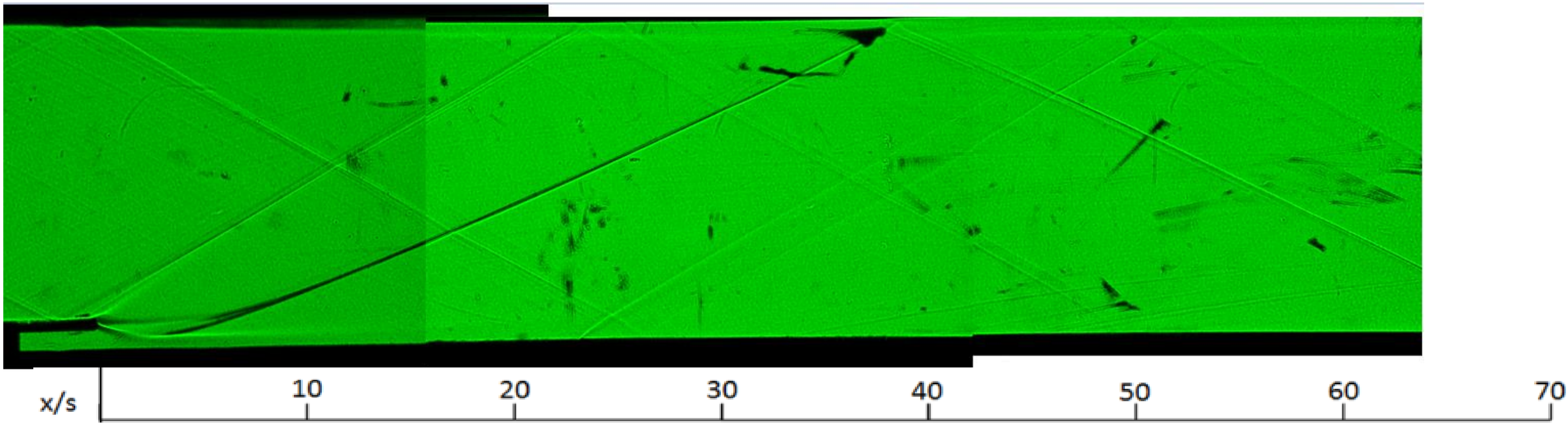
Flow

Film Louver





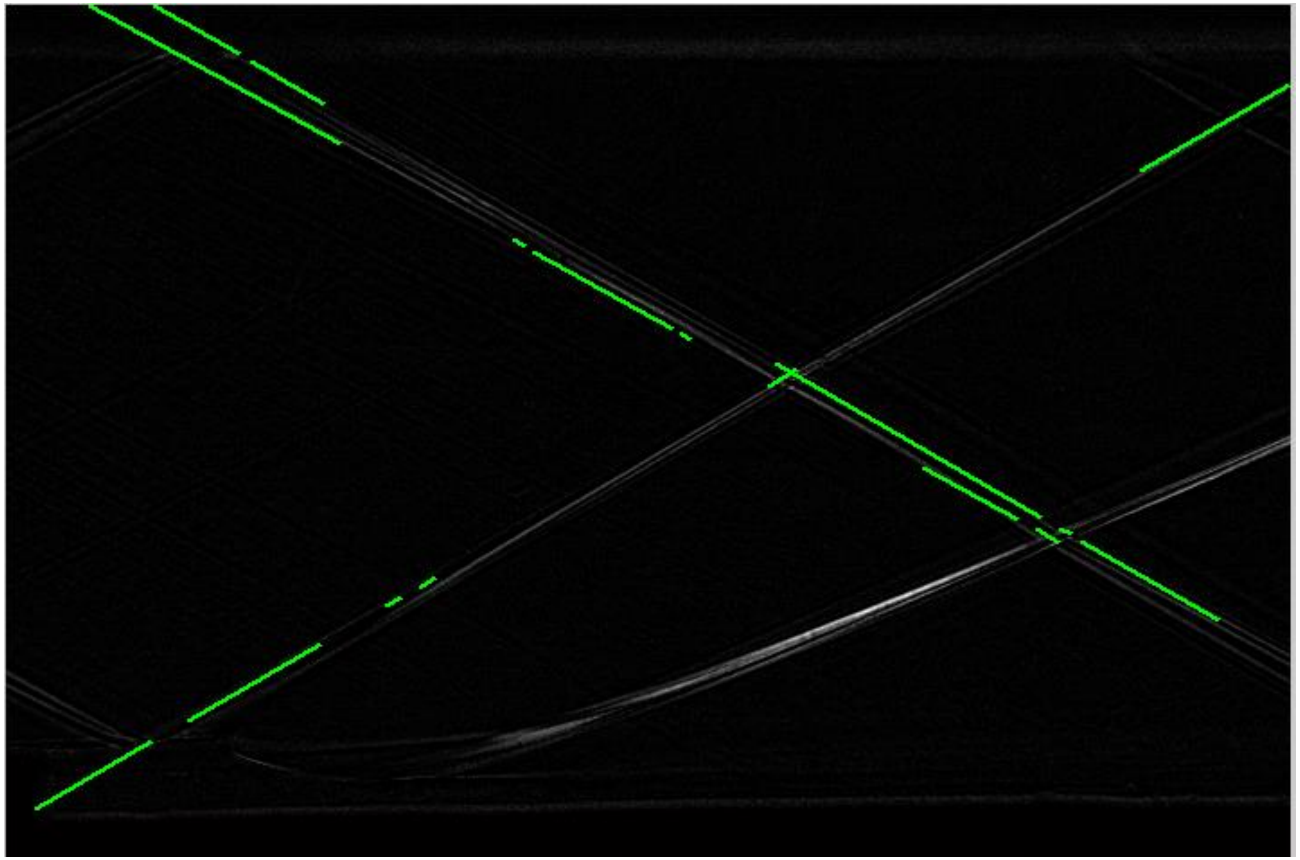
Schlieren Image of full test section: No Film



- Shear layer appears completely mixed out after x/s = 8
- Lip shock reflects off upper wall at x/s = 22.5
- Numerous blotches are window scratches

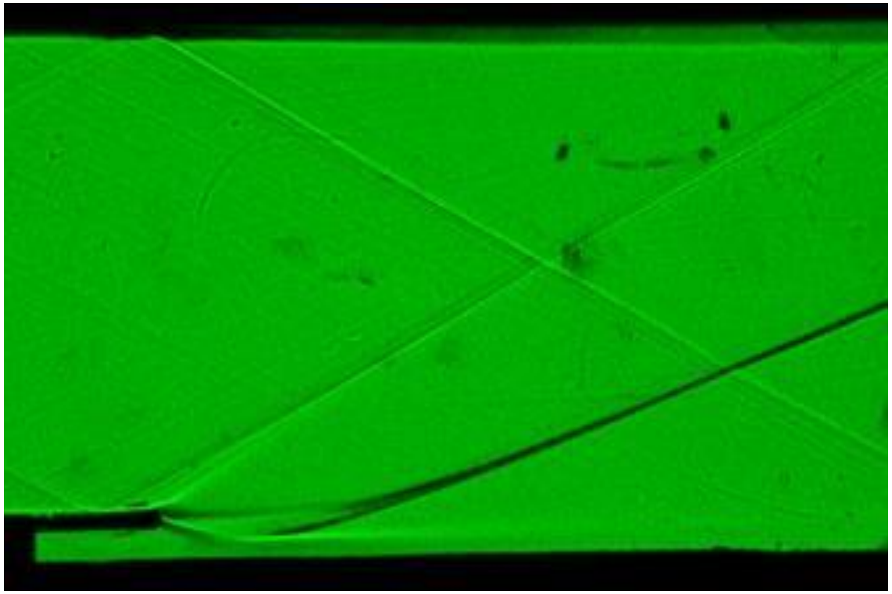
Automated Angle Detection

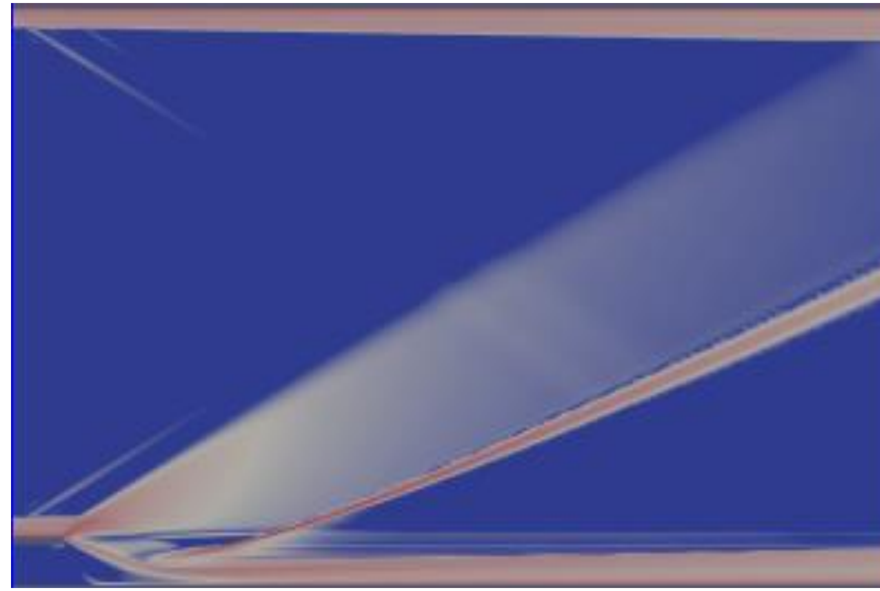
- Able to detect lines in an image using the Hough transform matlab functions



Case 0 ($M_{film} = 0$)

Comparison to CFD

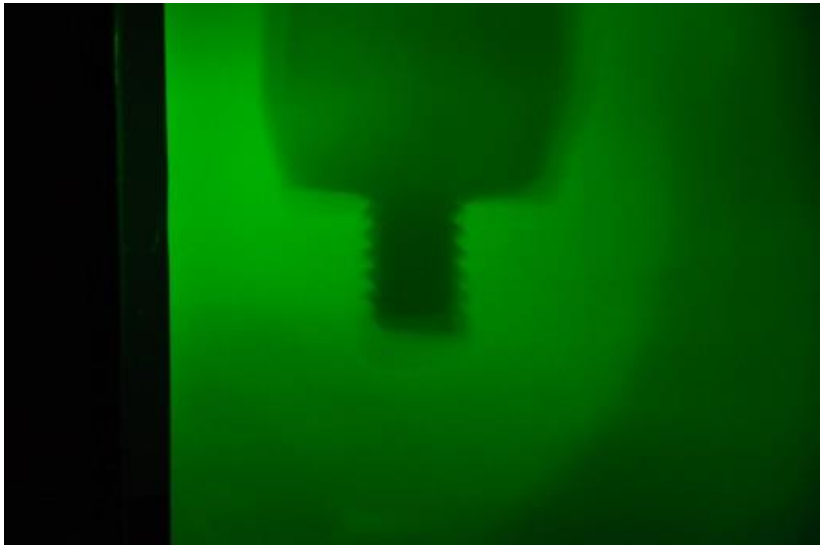




- Schlieren and CFD are qualitatively similar
  - Both show lip and reattachment shocks
  - Evidence of recirculation region
- Shock angles consistent within 5%
  - Lip shock $\theta = 30°$
  - Reattachment shock $\theta = 21°$
  -

Depth of Focus

In focus

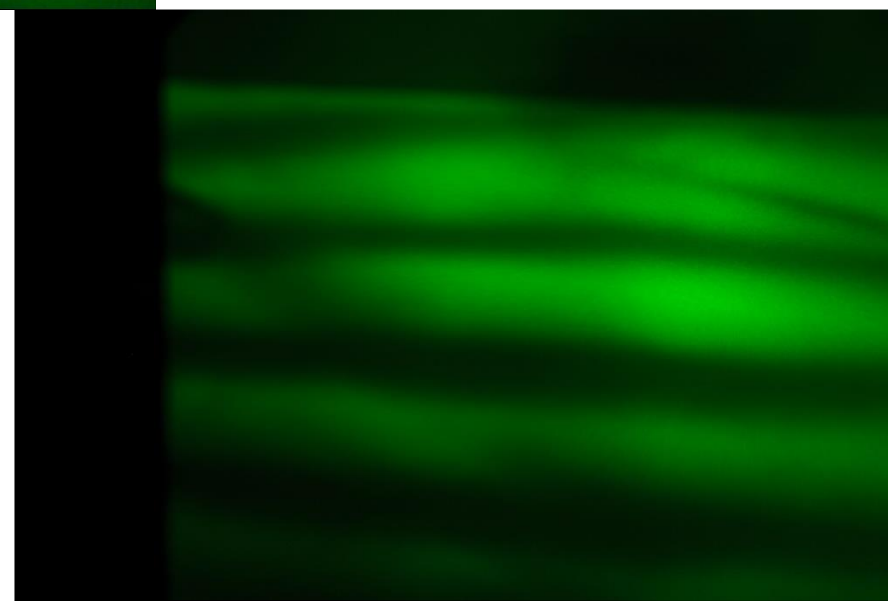


10 mm
out of focus

- Target is an 8-32 bolt
- Depth of Sharp focus is on the order of 10 mm
  - Much smaller than tunnel width (152 mm)
  - Insufficient to resolve small scale structures
  - But much better than regular schlieren

Focused Schlieren Sensitivity

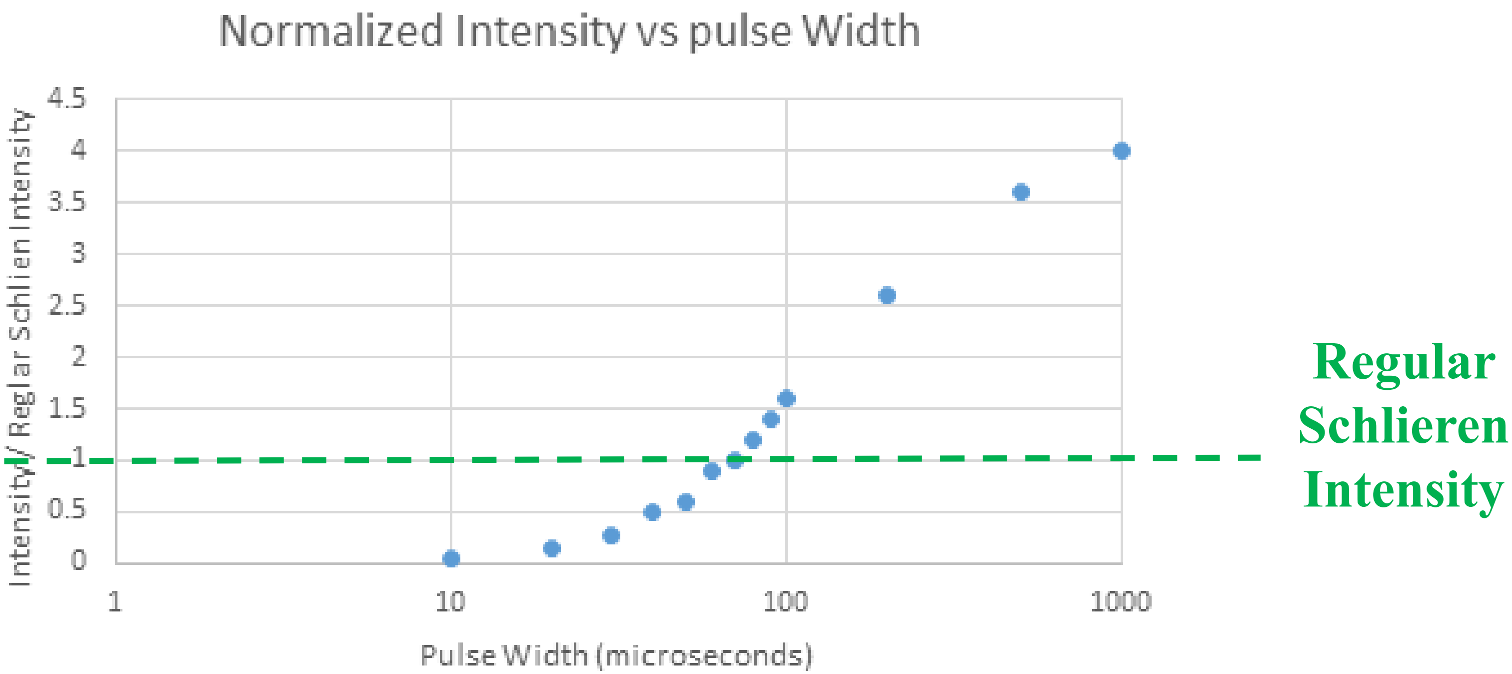
- **Focused schlieren video of butane gas stream in the test section**



No Film Case Focused Schlieren Minimum verifiable density gradient

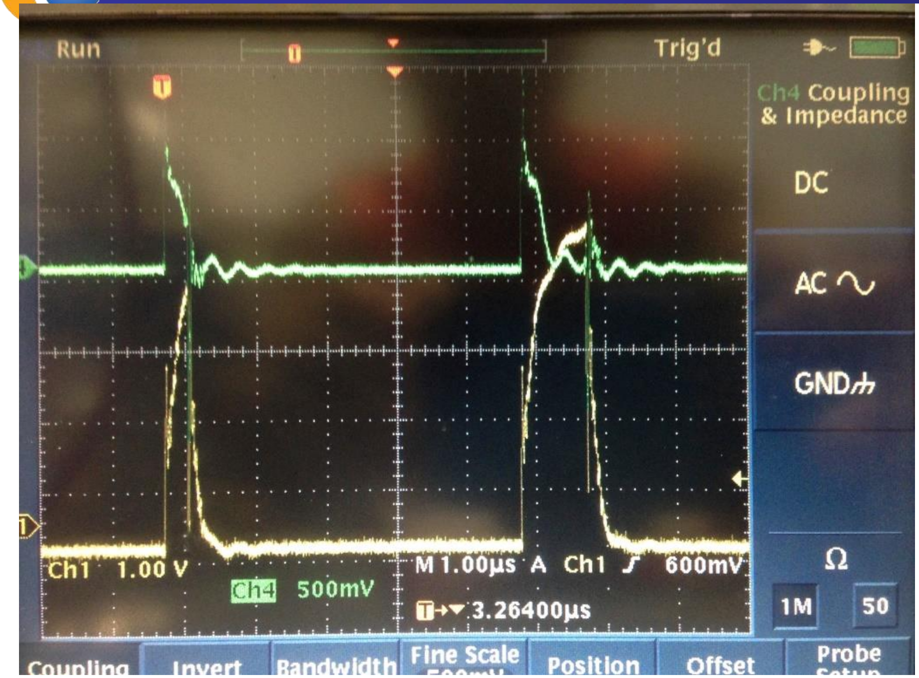
$$\sim 26\,\frac{kg}{m^4}$$

Power/Pulse Width Tradeoff



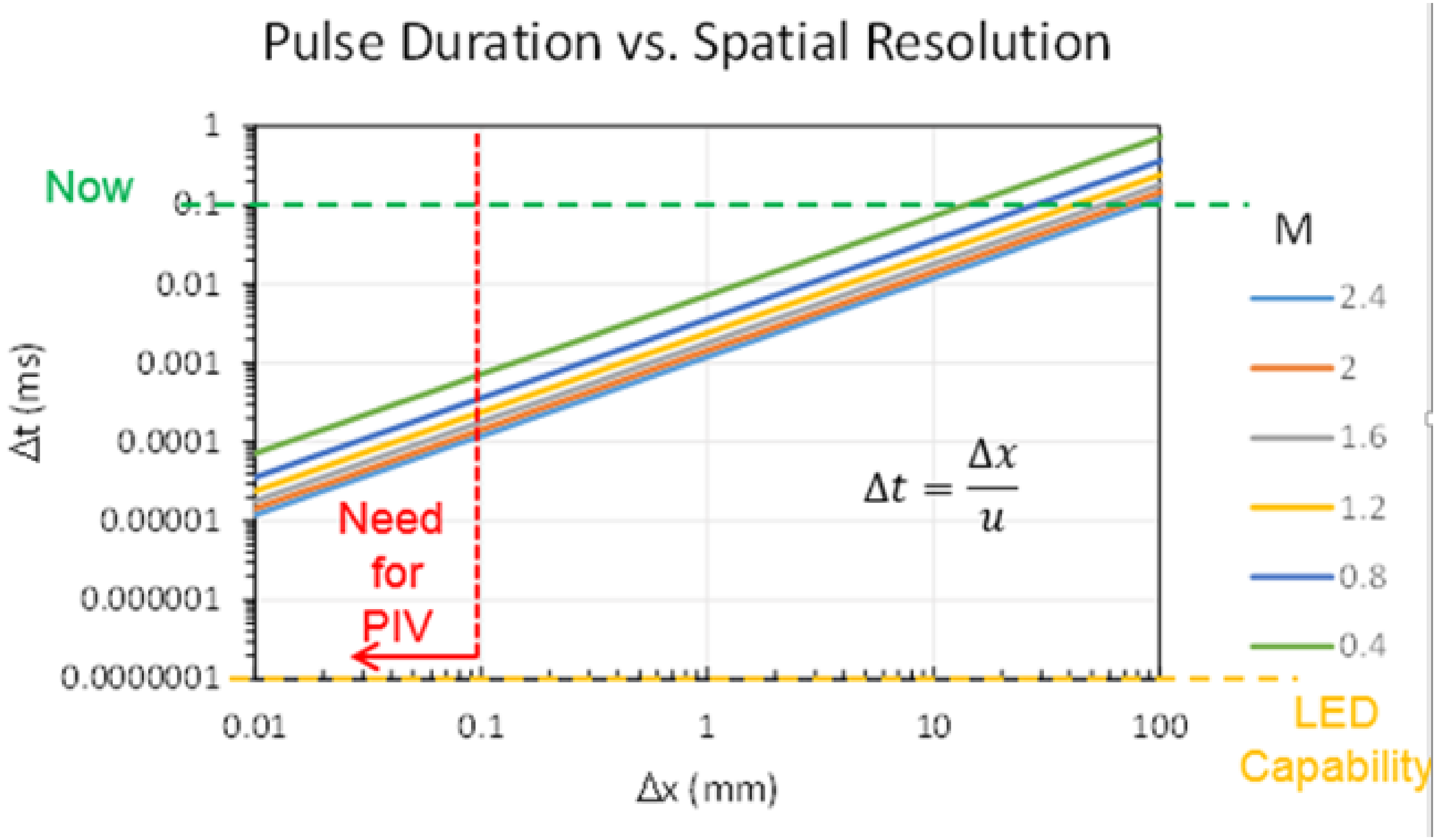
- The 70 μs pulse provided enough power to illuminate the test section

Amplifier → Transistor



- Yellow is the output of the amplifier (the gate input of the transistor) and green is the output of the transistor
- 1µs scale on left and 4µs scale on right
- Delayed response of transistor seems to be related to delayed rise to peak voltage in the amplifier (amplifier might need to be replaced)

Pulsed Light Source



- Pulse width needs to be dropped 3 orders of magnitude for PIV

Conclusions

- Status of current system :
  - Insufficient sensitivity to resolve turbulent density fluctuations
  - Insufficient depth of sharp focus to resolve turbulent structures
  - Insufficient temporal response to freeze flow

	Expected	Actual	Required
Sensitivity: Density Gradient ($\frac{kg}{m^4}$)	0.88	26	5
Depth of Sharp Focus (mm)	1	10	1
LED Pulse Width (μs)	5	70	0.1

Next Steps

- Regular Schlieren
  - Obtain more downstream images
- Main problem with focused schlieren system is rigidity
  - Focused schlieren very difficult to align precisely
  - Will provide better frame for Fresnel lens and source grid
- LED power supply
  - Some components don’t seem to behave as advertised
  - Will test with new components
  - Looking into alternative circuits

Acknowledgements

- The authors would like to thank the National Aeronautics and Space Administration and Melinda Nettles of the Marshall Space Flight Center for their support under NRA NNM13AA13G.

References

1. Vandercreek, Colin, Michael Smith, and Kenneth Yu. "Focused Schlieren and Deflectometry at AEDC Hypervelocity Wind Tunnel No. 9." *27th AIAA Aerodynamic Measurement Technology and Ground Testing Conference* (2010):.
2. Lawson, Michael, Michael Hargather, Gary Settles, Leonard Weinstein, and Sivaram Gogineni. "Focusing-Schlieren PIV Measurements of a Supersonic Turbulent Boundary Layers." *47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition* (2009).
3. Willert, C., B. Stasicki, J. Klinner, and S. Moessner. "Pulsed Operation of High-power Light Emitting Diodes for Imaging Flow Velocimetry."*Measurement Science and Technology Meas. Sci. Technol.* 21.7 (2010): 075402.